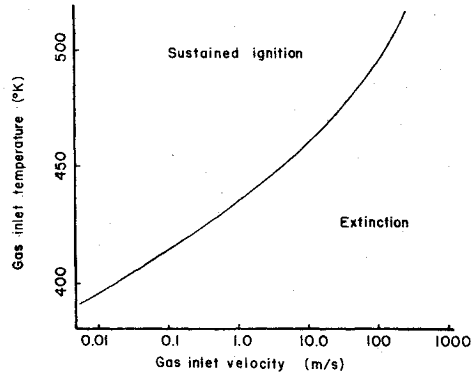

Fig. 1 Steady-state operation of reactor. Solid line represents minimum conditions to maintain sustained operation.

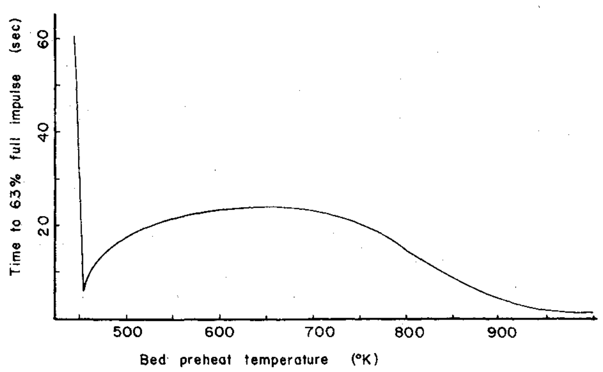

Fig. 2 Response time as a function of catalyst bed preheat: fuel feed rate = 0.6 g/s; feed temperature = 400 K.

For optimal response the exiting gas temperature should approach its steady state value as quickly as possible. Figure 2 shows results to achieve 63% of steady state impulse as a function of bed preheat for feed conditions corresponding to minimal values for sustained operation. The response time is a minimum at a moderate pre-heat temperature and increases with pre-heat temperature until very high pre-heat temperatures are introduced. At the minimum response time the ignition zone occurs at the end of the reactor. Increasing the bed pre-heat causes the reaction to move upstream. The hot combustion gases are then cooled as they heat the catalyst downstream of the combustion zone. The thermal mass of the catalyst bed is much greater than the flowing gases, slowing the desired response.

These results indicate that the optimal response is obtained when the combustion zone originates at the reactor outlet. Summarized in Table 1 are the changes the three control parameters have on the position of the combustion zone. The three parameters can be used to implement control strategies. For example, in a repetitive firing mode the response time may increase when there is insufficient time for the bed to cool to the desired temperature before the next firing. However, by increasing the fuel feed an appropriate amount the response time could be maintained constant, though the thrust would be increased.

The model presented here is able to account for the system response observed by Seifert et al. by assuming the catalyst bed is divided into two sections, a vaporization section 2 cm long and a reaction section 8 cm long. The applicability of the model suggests nitromethane-based systems with specified response characteristics are feasible, though the complexity of the control makes replacement of hydrazine-based systems unlikely.

Acknowledgment

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Some New Results of Chuffing in Composite Solid Propellant Rockets

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Introduction

CHUFFING is one of the low-frequency instabilities in solid propellant rockets functioning at low chamber pressures. In chuffing, the rocket motor experiences brief spurts of combustion and consequent pressure buildup, followed by periods of near ambient pressures in the combustion chamber. This period of dormancy can extend up to a few seconds. According to many earlier workers,[1-3] during the low-pressure induction period, slow reactions take place in a subsurface layer of the propellant which eventually reaches the temperature where a thermal explosion can occur. Rapid burning of this preheated layer is followed by a sudden ceasing of propellant combustion as the layers beneath it, being at low temperature, cannot sustain the process. While this theory projects the condensed phase reactions as solely responsible for chuffing, there are also those which bring in the importance of gas phase processes.[4]

Whereas the condensed phase reactions are known to be of paramount importance in cordite-like homogeneous propellants, their importance in composite propellant combustion is still being debated. Chuffing, however, has been observed with composite propellants also.[5,6] This prompts a re-examination of the role of the gas phase processes and the motor characteristics in chuffing. Also, the data on composite propellant chuffing have not been presented in as detailed a form as with cordite propellants.[1] The present work describes systematic experimental study to relate the chuffing frequency and pressure to such rocket motor parameters as the characteristic length (L^*) and the ratio (K) of burning surface area to throat area.

Experiment

The experimental setup is similar to the one described in Ref. 6. An L^*-motor consisting of a stainless steel cylinder and a piston which can be positioned in the cylinder to provide the desired value of L^* (characteristic length = volume of the combustion chamber/nozzle throat area) is used to burn end-burning solid propellant discs (see insert in Fig. 1). A strain-gage pressure transducer and associated signal conditioner

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and recorder system are used for obtaining the pressure-time trace during combustion.

A propellant (CP-2), whose composition is given in Table 1, was prepared for the sole purpose of studying the chuff. The particle size of ammonium perchlorate has been intentionally kept very small, which makes the propellant prone to unstable burning. For the same reason, there are no metallic additives in the propellant. The steady-state burning rate law as obtained from a strand burner and the theoretical value of the characteristic velocity are also included in Table 1. The pressure index in the burning rate law appears rather high for composite propellants, but it has been derived from low-pressure data only. Similar observation on CMDB propellants was made by Yount and Angelus ($n \sim 0.9$).[3]

Uniform ignition of the entire burning surface was achieved by coating the surface with a special ignition paste. Pilot ignition was effected by a pellet of high-energy, aluminized composite propellant powder. Other surfaces of the 5-6 mm thick propellant discs were inhibited by a conventional inhibitor compound.

Results and Discussion

In the L^*-motor used in the present experiments, for the fixed end-burning surface area of the propellant (A_b), the nozzle throat area (A_t) alone decides the steady-state equilibrium chamber pressure once the propellant characteristics are known. The desired range of L^* can then be set by locating the piston such that appropriate free volume ($V_c = L^* \cdot A_t$) is enclosed.

The raw data of chamber pressure vs time, as obtained in a series of test firings with CP-2 propellant, are shown in Fig. 1. The value of K was held constant for this set of firings. In each firing, the L^* varies by about 30 cms from ignition to burnout, corresponding to the consumption of the approximately 5.2-mm-thick propellant disc. The total range of L^* covered in these firings is from 30 to 250 cm. It is very clear from the traces that the chuffing varies systematically with L^*. While the frequency of chuffing decreases gradually with L^*, the pulse width and the pressure level increase. The behavior is so ordered that when a propellant disc of 30 mm thickness was used in a firing to cover the total range of L^*, the P_c-t trace reproduced the pattern from high-frequency, low-peak chuffing to the final stable combustion. This, in addition to supporting the reproducibility of the behavior, is also indicative of the fact that the nature of chuffing at any given L^* is independent of initial conditions.

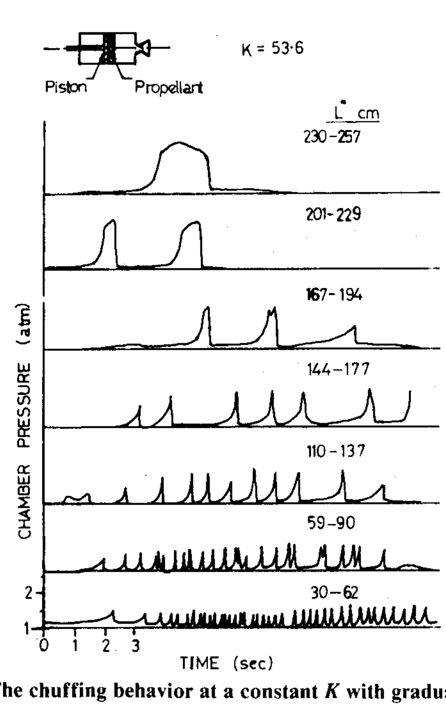

Fig. 1 The chuffing behavior at a constant K with gradual variation in L^*.

Figure 2, showing the variation of frequency of chuffing and average peak pressure of chuff pulses with L^*, summarizes the observations made on Fig. 1. The average peak pressure (P_p) is normalized with respect to the steady state pressure (P_{ss}), which is the constant chamber pressure corresponding to stable combustion at large L^*. Although the exact functional dependence of the different quantities is difficult to identify, the trend is smooth and distinct. Low-frequency instability in solid propellant rockets also shows such a dependence.[2,6]

By dividing the propellant thickness by the number of chuffs observed in a firing, the average thickness of surface layer (hereafter referred as "Reaction Layer") can be obtained. This, as described earlier, experiences gradual heatup and then bursts, giving rise to a pressure pulse. The variation of the reaction layer thickness with L^* is shown in Fig. 3. It may be noted that the reaction layer thickness is as deep as 2.6 mm when steady-state conditions prevail. The peak pressure level in the combustion chamber must have a relation with the

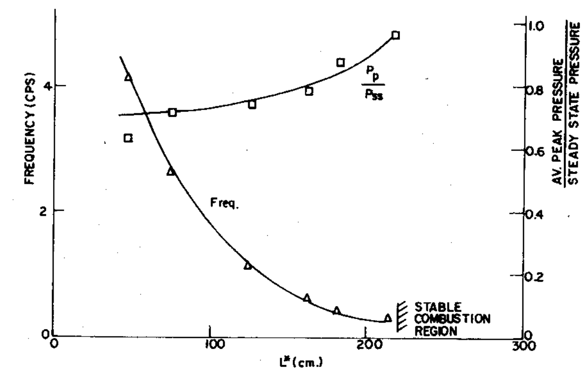

Fig. 2 Variation of chuffing frequency and peak pressure with L^*.

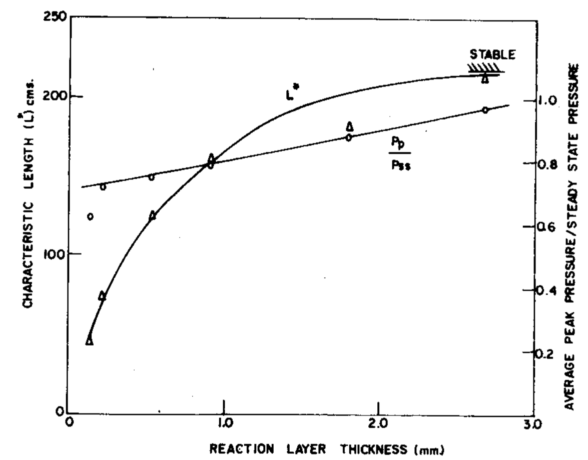

Fig. 3 Reaction layer thickness L^* and peak pressure.

Table 1 Characteristics of composite propellant (CP-2)

Composition, by weight, %	
Ammonium perchlorate	80.0
CTPB	13.4
Liquid paraffin	4.8
Other curing agents	1.8
Burning rate law, steady-state	$\dot{r} = 0.166\, p^{0.588}$ cm/s $1.0 \leq p \leq 0$ atm
Density	$\rho p = 1.54$ gm/cc
	Theoretical estimates
Characteristic velocity	$C^* = 1312$ m/s
Flame temperature	$T_f = 2290$ K

reaction layer thickness as long as the rate of burning during the pulse is fast enough. A plot of peak pressure vs reaction layer thickness, also shown in Fig. 3, exhibits a remarkably good linearity.

Experiments conducted at higher levels of K, but at comparable L^*-range, have shown that the chuffing frequency is nearly the same, but that the peak pressure level increases with K (resembling the steady-state behavior of the rocket). The L^*-K (or equivalent chamber pressure) boundary for transition from chuffing to stable combustion is similar to the ones identified by earlier workers.[6,7]

Conclusions

From the results of the experiments conducted to study the chuffing behavior in composite propellants, it can be concluded that the frequency of chuffing and the pressure amplitudes vary systematically with L^*. The experiments have enabled the measurement of reaction layer thickness at different L^* ranges. The level of L^* seems to influence the reaction layer thickness, which gives rise to a definite pressure pulse for sufficiently low values of K. Any description of chuffing, therefore, must consider motor characteristics such as L^* and K in addition to the condensed phase processes.

Acknowledgment

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Estimate of the Probability of a Lightning Strike to the Galileo Probe

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MOST lightning strikes to aerospace vehicles occur in or near clouds. Because the Galileo entry probe will spend most of its operational lifetime in the clouds of Jupiter, and because Jupiter is known to have lightning activity,[1] it seems appropriate to consider the risk of a lightning strike to the probe. A strike to the probe could cause physical damage to the structure and/or damage to the electronic equipment aboard the probe, depending on the location of the strike and the size and shape of the current pulse.[2,3] It is possible that the instrumentation failures that occurred on all four Pioneer Venus entry probes at an altitude of 12 km were due to an external electric discharge.[4]

Although a strike to a vehicle is more probable when the vehicle is in a thundercloud, strikes to vehicles can and do occur when the vehicle is within a cloud that is not producing lightning flashes. Such strikes are often caused by the presence of the vehicle, i.e., strikes occur in a region where no strikes occur before or after the presence of the vehicle.[5,6] One of the more spectacular examples of an aerospace vehicle triggering lightning flashes was the launch of Apollo 12 (Ref. 3). It was struck twice as it rose through the cloud layer above Cape Canaveral on Nov. 14, 1969. No lightning was observed before or after the launch.[3] The fundamental cause of a strike to a vehicle is believed to be the intensification of a preexisting electric field by the vehicle. Consequently, large vehicles can cause strikes where smaller vehicles would not.

No general theory exists for predicting the strike frequency to a vehicle. However, aircraft experience is available and is used here to develop an estimate of the strike probability. The estimation of the strike probability P_s naturally breaks into two parts, the probability P_t of a strike occurring while a vehicle is penetrating a thundercloud, and the probability P_c of a strike occuring while a vehicle is penetrating clouds in which no activity is observed prior to entry. To estimate P_c, the data tabulated in Ref. 2 for Air Force and Commercial aircraft operating in the United States will be used. A better estimate for P_c could be obtained if data on probability of a strike per hour of operation in nonthunderstorm clouds were available. Unfortunately, no value for that parameter could be found. Air Force aircraft suffer fewer strikes per hour of operation than do commercial aicraft because Air Force operations are curtailed in poor weather. For example, Air Force trainer aircraft are struck once per 3×10^5 h of operation. Air Force bombers are struck only once per 5×10^4 h. In Europe, the F-4 fighter aircraft is struck once per 1×10^4 h. Commercial aircraft flying in the United States are struck once per 3×10^3 h. The implication of these values is that as the fraction of time spent in clouds increases, so does the probability of a strike. The high rate of strikes to commercial planes is believed to be due to the commercial need to fly in all types of weather. It should be noted, however, that commercial aircraft do make every effort to avoid thunderstorm clouds and that commercial aircraft spend much operation time above clouds where there is little possiblity of a strike. In contrast to spending most of its operation time ouside the clouds, the Galileo Probe will spend most of its operational time in the clouds of Jupiter. If the electrification of the Jovian clouds is similar to that of terrestrial clouds, then P_c will be at least 3×10^{-4} per h.

To get an estimate of P_t, the results of the Storm Hazards program at the Langley Research Center will be used.[7] In that flight test program, an F-106B aircraft was flown through thunderstorms a total of 421 times. The aircraft received 176 direct strikes and 54 near misses. Therefore, a reasonable estimate for P_t is 0.42.

Next, the probability estimates should be corrected for differences in lightning activity on the two planets and for the differences in size between the Galileo Probe and the aircraft used to derive the estimates.

It is expected that the probabilities of a strike depend on the specific planetary flash rate, i.e., the global average number of flashes per square kilometer per hour. In Ref. 1 it is shown that the specific flash rate is similar for both planets. Hence, no correction for this parameter is needed.

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